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Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: A review

Zainal Alimuddin Bin Zainal Alauddin [a,1], Pooya Lahijani [a,1], Maedeh Mohammadi [b,2], Abdul Rahman Mohamed [b,*]

[a] School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia
[b] School of Chemical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia

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ABSTRACT

A literature review on gasification of lignocellulosic biomass in various types of fluidized bed gasifiers is presented. The effect of several process parameters such as catalytic bed material, bed temperature and gasifying agent on the performance of the gasifier and quality of the producer gas is discussed. Based on the priorities of researchers, the optimum values of various desired outputs in the gasification process including improved producer gas composition, enhanced LHV, less tar and char content, high gas yield and enhanced carbon conversion and cold gas efficiency have been reported. The characteristics and performance of different fluidized bed gasifiers were assessed and the obtained results from the literature have been extensively reviewed. Survey of literature revealed that several industrial biomass gasification plants using fluidized beds are currently conducting in various countries. However, more research and development of technology should be devoted to this field to enhance the economical feasibility of this process for future exploitations.

Contents

1. Introduction

Rapid development of technology and industrialization has faced mankind with two major concerns: depletion of fossil energy resources and deterioration of the environment. Fossil fuels are the most common energy sources used in the world. It has been reported that over 80% of the energy consumption counts for fossil

* Corresponding author. Tel.: +60 4 599 6410; fax: +60 4 594 1013.
E-mail addresses: mezainal@eng.usm.my (Z.A.B.Z. Alauddin), pooya.lahijani@gmail.com (P. Lahijani), mohammadi_fanni@yahoo.com (M. Mohammadi), chrahman@eng.usm.my (A.R. Mohamed).
[1] Tel.: +60 4 593 7788; fax: +60 4 594 1025.
[2] Tel.: +60 4 599 6410; fax: +60 4 594 1013.

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fuels [1]. However, there are some crucial problems associated with such fuel sources. Fossil fuels emit significant amount of pollutants such as CO_2, NO_x and SO_x into the atmosphere [2]. Combustion of fossil fuels produces large amount of CO_2 which is considered for its greenhouse effect and promotion of global warming [1]. Besides, energy consumption has increased 17-fold in the last century and with the present rate of energy consumption, it is estimated that the world's oil reservoir will be diminished by 2050. Meanwhile, the cost of fossil fuel is globally increasing [2,3]. These issues remind us the need to find alternative fuel resources which are renewable, sustainable and count for eco-friendly fuels.

Among all of the renewable resources, biomass is the only renewable source of carbon which can be converted to solid, liquid and gaseous product through various conversion processes [4]. Currently, biomass is the fourth largest source of energy in the world after coal, petroleum and natural gas and provides about 14% of the world's energy consumption [3]. Biomass wastes are mostly burnt in open air or dumped which generate pollutants including dust, acid rain gases such as NO_x and SO_x and large amount of methane which is a more potent greenhouse gas than CO_2. Therefore, in developed countries there is a growing trend towards the use of biomass based energies [1]. These technologies which use waste or plant matter to produce energy, emit less greenhouse gas than fossil fuels and are cost wise competitive with conventional energy resources. One of the promising technologies which utilizes the biomass wastes is biomass gasification. The gasification of lignocellulosic biomass has attracted considerable attention among various thermo-chemical conversion technologies as it offers high conversion efficiency [5]. It is one of the strategies for exploitation of renewable fuels and power generation. Biomass gasification also assists the bioremediation plans as it converts the biomass wastes into clean fuel gases and biofuels.

Gasifiers are categorized into four main types of fixed bed, moving bed, fluidized bed and entrained flow [6]. There are some disadvantages associated with both fixed bed and moving bed gasifiers due to the generation of large quantities of tar and char which are resulted from low and non-uniform heat and mass transfer between solid biomass and gasifying agent within the reactor [7,8]. In contrast, fluidized bed gasifiers provide excellent mixing and gas–solid contact which enhances the reaction rate and conversion efficiencies. Besides, use of bed material as heat transfer medium and catalyst reduces the tar content of producer gas and improves its quality [9].

The purpose of current paper is to present a detailed review on gasification of lignocellulosic biomass in various fluidized bed gasifiers. The effect of several process parameters on the quality and composition of the producer gas are reviewed. Biomass gasification process in various types of fluidized bed reactors is discussed and the collected results from the literature are reported.

2. Important process parameters in fluidized beds

Design and operation of a gasifier requires understanding of the effect of various types of biomass and operation parameters on the performance of the system. Lignocellulosic biomass differs greatly in their physical, chemical and morphological properties which affect the characteristics of the gasification process [10]. Also, the choice of a biomass is significantly depended on its heating value [11]. Biomass wastes with high heating value contribute to more energy recovery and better system performance in terms of efficiency and economy. However, effective heat and mass transfer properties of fluidized beds provide the possibility of using various types of biomass wastes with different compositions and heating values [12]. Table 1 depicts the ultimate and proximate analysis of various lignocellulosic biomass.

Several researches have been conducted on biomass gasification for improving the producer gas composition (H_2, CO, CO_2, CH_4, and C_nH_m), obtaining a gas with considerable LHV, reducing the tar and char content of the effluent stream and enhancing the gas yield, cold gas efficiency and carbon conversion. It should be considered that these gasification performance indexes are in trade-off relationship. For example, increasing the bed temperature to reduce the tar concentration will significantly reduce the LHV and cold gas efficiency. Thus, it is impossible to meet all the performance indexes at their desirable values at the same time. Various researchers have put their first priorities on different indexes however; there are some significant operation parameters that should be carefully determined to obtain a gas stream with desirable properties. The main process parameters and their effect

Table 1
The ultimate and proximate analysis of various lignocellulosic biomass.

Biomass type	Ultimate analysis (db, % w/w)					Proximate analysis (% w/w)				LHV (MJ/kg)	Ref.
	C	H	O	N	S	Ash	VM	FC	M		
Cedar wood	51.10	5.90	42.50	0.12	0.02	0.3	80–82	18–20	[a]	19.26	[13]
Wood sawdust	46.2	5.1	35.4	1.5	0.06	1.3	70.4	17.9	10.4	18.81	[14]
Olive oil residue	50.7	5.89	36.97	1.36	0.3	4.6	76	19.4	9.5	21.2	[15]
Rice husk	45.8	6.0	47.9	0.3	–	0.8	73.8	13.1	12.3	13.36	[16]
Rice straw	38.61	4.28	37.16	1.08	0.65	12.64	65.23	16.55	5.58	14.40	[17]
Pine sawdust	50.54	7.08	41.11	0.15	0.57	0.55	82.29	17.16	[a]	20.54	[18]
Spruce wood pellet	49.3	5.9	44.4	0.1	–	0.3	74.2	17.1	8.4	18.5	[19]
Coffee husk	46.8	4.9	47.1	0.6	0.6	1.0	74.3	14.3	10.4	16.54	[16]
Coffee ground	52.97	6.51	36.62	2.8	0.05	1.0	71.8	16.7	10.5	22	[20]
Larch wood	44.18	6.38	49.32	0.12	–	0.12	76.86	14.86	8.16	19.45	[21]
Grapevine pruning waste	46.97	5.8	44.49	0.67	0.01	2.06	78.16	19.78	[a]	17.91	[22]
Jute stick	49.79	6.02	41.37	0.19	0.05	0.62	76–78	21.4–23.4	[a]	19.66	[23]
Sugar-cane bagasse	48.58	5.97	38.94	0.2	0.05	1.26	67–70	28.74–30.74	[a]	19.05	[23]
Corn cob	40.22	4.11	42.56	0.39	0.04	2.97	71.21	16.11	9.71	16.65	[24]
Peach stone	51.95	5.76	40.7	0.79	0.01	0.65	81.3	18.1	8.53	21.6	[25]
Wheat straw	46.1	5.6	41.7	0.5	0.08	6.1	75.8	18.1	[a]	17.2	[26]
Cotton stem	42.8	5.3	38.5	1.0	0.2	4.3	72.3	15.5	7.9	15.2	[27]
Straw	36.57	4.91	40.70	0.57	0.14	8.61	64.98	17.91	8.5	14.6	[28]
Camphor wood	43.43	4.84	38.53	0.32	0.1	0.49	72.47	14.75	12.29	17.48	[6]
Beech wood	48.27	6.36	45.2	0.14	–	0.8	81	18	[a]	19.2	[29]
Switchgrass	47	5.3	41.4	0.5	0.1	4.6	58.4	17.1	20	18.7	[30]

VM: volatile matter; FC: fixed carbon; M: moisture.
[a] Dry basis.

on the quality of the effluent stream of the gasifiers are discussed in the following section.

2.1. Effect of bed materials

Bed materials are of great importance in fluidized bed gasifiers. They act as heat transfer medium but their major role involves in tar cracking which avoids complicated downstream tar removal process [24]. The presence of catalyst in the bed material during biomass gasification promotes several chemical reactions which influences the composition and heating value of the producer gas. It also reduces the tar yield and prevents solid agglomeration tendency of the bed [5].

The catalytic reforming reactions through which tar is converted into useful gaseous compounds are summarized as follows [31,32]:

$$C_nH_m(\text{tar}) + nH_2O \leftrightarrow (n + m/2)H_2 + nCO$$

$$C_nH_m(\text{tar}) + nCO_2 \leftrightarrow (m/2)H_2 + 2nCO$$

$$C_nH_m(\text{tar}) + (n/2 + m/4)O_2 \leftrightarrow (m/2)H_2O + nCO$$

$$C_nH_m(\text{tar}) \leftrightarrow (m/2)H_2 + nC$$

Generally, three main groups of catalysts are implemented to remove tar from the producer gas [21,32]: (1) natural catalysts such as dolomite and olivine; (2) alkali-based catalysts such as (Li, Na, K, Rb, Cs and Fr) and (3) metal-based catalyst such as nickel catalysts.

Dolomite is the most commonly used catalyst which effectively removes heavy hydrocarbons from the gas stream [21]. It also decreases agglomeration in fluidized bed while using biomass with high alkali content. But, the undesired property of dolomite is its quick calcination in the gasifier which consequently results in a gas with high particulate [33]. Olivine is reported to be less effective than dolomite [33] but its resistance against attrition is more than that of dolomite [21,33]. Alkali-based catalysts (Li, Na, K, Rb, Cs and Fr) are able to improve the gasification rate and reduce the tar content of the producer gas. However, difficulty in recovery, high cost and agglomeration at high temperatures are some of the disadvantages of the alkali-based catalysts [21]. Metal-based catalysts are also highly effective in removing tar and improve the quality of the producer gas. The main problems associated with this type of catalysts are carbon deposition and nickel particle growth, which cause catalyst deactivation [21].

Asadullah et al. [13] compared the performance of the heterogeneous catalyst of $Rh/CeO_2/SiO_2$ in a fluidized bed gasification system to that of dolomite, steam reforming catalyst (G-91) and inert bed materials while the ER was set at 0.31 and the bed temperature was in the range of 823–973 K. It was observed that the tar content of the producer was completely negligible while using $Rh/CeO_2/SiO_2$ as the bed material. Whereas, the tar concentration of about 30, 113 and 139 g/m^3 was obtained with G-91, dolomite and inert bed materials, respectively. It was also concluded that in the case of $Rh/CeO_2/SiO_2$ catalysts, the efficiency of cold gas was about 71% more than others cases. Also, little char and coke were observed in the experiments with the $Rh/CeO_2/SiO_2$ as catalysts. In another set of experiments conducted by Miccio et al. [19], the effect of four different catalysts of quartz, olivine, dolomite and Ni-alumina on tar content of the producer gas was studied at ER of 0.17 and bed temperature of 870 °C. In their experiments, tar concentrations of 19.2, 13.2, 11.4 and 9 g/m^3 were obtained for quartz, olivine, dolomite and Ni-alumina, respectively. It was concluded that the presence of catalyst increased the hydrogen concentration in the producer gas and also the total gas yield was slightly improved. In another investigation conducted by Weerachanchai et al. [21], the performance of three different bed materials of calcined limestone, calcined concrete waste and silica sand was evaluated. It was observed that calcined limestone was the most effective catalyst for tar adsorption at 650 °C. The obtained results showed that calcined limestone and calcined concrete waste improved the H_2 and CO_2 content of the producer gas, whereas silica sand increased the CO content. Skoulou et al. [34] used quartz sand and olivine as bed materials in a bubbling fluidized bed gasifier at ER of 0.2–0.4 and bed temperature of 750–850 °C. They concluded that although quartz sand is a cheap and abundant material, it caused severe defluidization due to its tendency to tar formation at temperatures below 800 °C. They replaced quartz sand with olivine and observed that at low gasification temperature of 750 °C and ER of 0.2, components of tar were thermally broken down and released H_2 and CO, under the catalytic effect of iron-based olivine. Li et al. [35] investigated the effect of bed material on tar removal efficiency in a circulating fluidized bed. They used silica sand and a commercial Ni-alumina catalyst as bed material. At the bed temperature of 800 °C, the amount of tar reduced from 0.4 g/m^3 to 0.15 mg/m^3, as silica sand was replaced with Ni-alumina catalyst.

2.2. Effect of bed temperature

Bed temperature is one of the most important operation parameters which affect both the heating value and producer gas composition. Based on Le Chatelier's principle, the effect of temperature on producer gas composition depends on the thermodynamic behavior of the reactions. High temperatures improve product formation in endothermic reactions whereas they favor reactants in exothermic reactions. The main reactions that occur during gasification can be summarized as follows [17,21]:

$$\text{Oxidation}: \quad C + O_2 \leftrightarrow CO_2 \qquad \Delta H = +408.8\ \text{kJ/mol}$$

$$\text{Partialoxidation}: \quad 2C + O_2 \leftrightarrow 2CO \qquad \Delta H = +246.4\ \text{kJ/mol}$$

$$\text{Steamreforming}: \quad CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H = -206\ \text{kJ/mol}$$

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \qquad \Delta H = -165\ \text{kJ/mol}$$

$$\text{Water-gas}: \quad C + H_2O \leftrightarrow CO + H_2 \qquad \Delta H = -131\ \text{kJ/mol}$$

$$\text{Boudouard}: \quad C + CO_2 \leftrightarrow 2CO \qquad \Delta H = -172\ \text{kJ/mol}$$

$$\text{Water-gasshiftreaction}: \quad CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H = -41.98\ \text{kJ/mol}$$

$$C + 2H_2O \leftrightarrow CO_2 + 2H_2 \qquad \Delta H = +100\ \text{kJ/mol}$$

In fact, the main objective of the gasification process is to generate a combustible gas enriched in CO, H_2 and CH_4 with medium to high LHV which is suitable for further exploitation in internal combustion engines and turbines [34]. It has been stated that increasing the gasification temperature reduces the gas heating value. The necessary heat for gasification is provided by combustion enthalpy of the biomass, therefore high temperature improves biomass combustion which consequently results in more CO_2 and N_2 production and low heating value [36]. Also, high bed temperatures improve carbon conversion and steam cracking and reforming of tars which result in less char and tar formation and high gas yields [37,38].

Lv et al. [18] studied the effect of bed temperature on carbon conversion, gas yield and LHV. It was reported while increasing the

bed temperature, the carbon conversion efficiency improved from 78.17 to 92.59% and also the gas yield increased from 1.43 to 2.53 m^3/kg. As the temperature was raised from 700 to 900 °C, LHV of the gas reduced from 7.94 to 7.36 kJ/m^3. Narvaez et al. [31] investigated the effect of bed temperature (700–850 °C) on composition, tar content and LHV of the producer gas. They reported that in the studied temperature range, the H_2 content increased from 5 to 10%, CO increased from 12 to 18%, CO_2 decreased from 15.7 to 14% and CH_4 and C_nH_m contents were nearly constant. It was also observed that as the temperature increased, the tar content of the producer gas gradually reduced due to tar cracking and steam reforming reactions at high temperatures. It was also reported that the LHV of the producer gas was slightly increased due to the increase of H_2 and CO content. In another set of experiment conducted by Pinto et al. [37], co-gasification of coal and biomass in the bed temperature range of 750–890 °C was studied. It was observed that increasing the temperature led to an increase of about 70% in H_2 concentration, whereas a decrease of around 30% was obtained in CH_4 concentration. It was also reported that the char formation was reduced by 9% at high temperatures. The reduction in char yield confirmed improved carbon conversion while increasing bed temperature. Wu et al. [36] investigated rice husk gasification at 700–800 °C. It was reported that as the temperature was raised from 700 to 800 °C, H_2 concentration increase from 5.37 to 7.46%, CO reduced from 20.62 to 16.53%, CH_4 concentration varied from 5.79 to 4.79% and CO_2 increased slightly from 15.52 to 16.08%. The gas LHV also reduced from 6.47 to 5.54 MJ/m^3 as the temperature was elevated from 700 to 800 °C. Kumar et al. [39] also studied the effect of gasification temperature in the range of 650–850 °C. They obtained maximum carbon conversion of 82% and energy efficiency of 96% at 850 °C. It was also concluded that increasing the bed temperature from 650 to 850 °C improved H_2 concentration from 4 to 15%.

2.3. Effect of gasifying agent

Fluidized biomass gasification has been performed using various gasifying agents such as air, steam, oxygen–steam, air–steam, O_2-enriched air and oxygen–air–steam [40]. The technology of biomass air gasification boosts the feasibility of the gasification process and has been developed for industrial application. However, it generates a producer gas highly diluted by nitrogen with LHV of 4–6 MJ/m^3 and H_2 content of 8–14 vol.% which seems to be useful for electricity production or heat generation [9,40,41]. Biomass O_2-enriched air gasification provides a gas with medium heating value but, it requires oxygen production equipments which increases the cost of gasification process. Biomass steam gasification is capable of producing a fuel gas with heating value of 10–16 MJ/m^3 and H_2 content of 30–60 vol.% [28]. However, endothermic reactions involved in this process reduce the bed temperature and additional equipments and energy are required to increase the temperature to above 700 °C [42]. In steam–oxygen gasification, the necessary heat is provided through partial oxidation reactions. The produced gas has a high H_2 content and the problem of dilution with nitrogen is avoided but the high cost of pure O_2 makes the process unfavorable for industrial applications [40].

For a defined biomass flow rate, two ratios should be determined for the analysis of the process: equivalence ratio (ER) in air or oxygen gasification and steam to biomass ratio (SB) in steam gasification process.

2.3.1. Equivalence ratio

Equivalence ratio (ER) is one of the most important operation parameters involved in air biomass gasification. It is defined as the actual air to biomass weight ratio divided by stoichiometric air to biomass weight ratio needed for complete combustion [31].

High degree of combustion occurs at high ER which supplies more air into the gasifier and improves char burning to produce CO_2 instead of combustible gases such as CO, H_2, CH_4 and C_nH_m. Also, increasing the ER results in a decrease in the LHV of the producer gas because it hinders the production of CH_4 and other light hydrocarbons which have relatively large heating values. Besides, at high ER nitrogen provided by air dilutes the producer gas which in turn results in its low energy content [43]. Studies have shown that too small ER is also unfavorable for biomass gasification as it lowers the reaction temperature [18]. Therefore, an optimum value for ER in biomass gasification exists in the range of 0.2–0.4 which differs according to various operation parameters [31]. Selection of the suitable ER is somehow depended on the producer gas subsequent application. When the raw producer gas is going to be burnt in downstream furnaces, tar is not a serious issue also, the gas should have a high heating value, therefore the gasifier can be operated at the minimum ER of about 0.2. In the case of temperatures lower than 850 °C, tar yield is high and ER should be increased to about 0.3–0.4 to compensate such negative effects [31].

Lv et al. [18] studied the effect of ER on gas yield and LHV. They varied the ER from 0.19 to 0.27 and realized that the variation of ER could be divided into two stages of 0.19–0.23 and 0.23–0.27. In the first stage, the gas yield increased from 2.13 to 2.37 m^3/kg and the gas LHV increased from 8.82 to 8.84 MJ/m^3. It was observed that in the second stage, the LHV and gas yield decreased due to the improvement of the oxidation reactions which also decreased the concentration of CO, CH_4 and C_nH_m and increased the CO_2 concentration. So, the value of 0.23 was selected as the optimum ER. In another set of experiments conducted by Narvaez et al. [31], ER was varied in the range of 0.25–0.45 to find the optimum ER. It was observed that increasing the ER reduced the amount of H_2, CO, CH_4 and C_2H_2. Maximum H_2 concentration of 10% was obtained at ER of 0.26. They also realized that while the ER was increased the tar content of the producer gas was gradually decreased and at ER of 0.45, minimum tar concentration of 2–7 g/m^3 was achieved. They obtained LHV of 5.2–7 MJ/m^3 and 3.5–4.5 MJ/m^3 at ERs of 0.25 and 0.45, respectively. It was also concluded that the gas yield was in a direct relationship with ER. Similar trends were obtained by Li et al. [17] who investigated the co-gasification of biomass and coal while the ER was in the range of 0.31–0.47. They also explained that as ER increased, more oxygen was introduced into the gasifier which enhanced the combustion and increased the bed temperature from 948 to 1026 °C. Skoulou et al. [34] also studied the effect of ER variation (0.2–0.4) as one of the most important operation parameters on the quality of the producer gas. They reported favored concentration of CO at low ER of 0.2 and its hindered production at ER of 0.4 because of complete oxidation of carbon to CO_2. Also, H_2 production peaked at ER of 0.2. Lower heating value of the producer gas was obtained at high ER which was due to the promotion of the oxidation reaction and dilution of the producer gas with N_2. Mansaray et al. [43] investigated the effect of ER on the gasifier performance. They concluded that as the ER was increased from 0.25 to 0.35, the concentration of CO_2 and N_2 also increased while the concentration of the combustible gases gradually decreased. They also realized that the gas yield increased from 1.3 to 1.98 m^3/kg as the ER was raised from 0.25 to 0.35.

2.3.2. Steam to biomass ratio

Steam to biomass ratio (SB) which is defined as the flow rate of the steam fed into the gasifier divided by the biomass flow rate is one of the important process parameters involved in steam gasification [40].

An experimental study on biomass air–steam gasification was conducted by Lv et al. [18]. They investigated the effect of SB on the

quality of the producer gas in the range of 0–4.04. It was observed that the introduction of steam to the system improved the gas yield, LHV and carbon conversion efficiency. They reported the SB range of 1.35–4.04 as the optimum SB in which the CO, CH_4 and C_2H_2 content of the producer gas decreased, whereas the CO_2 and H_2 concentration gradually increased. It was explained that in this SB range, more steam reforming reactions of CO, CH_4 and C_2H_2 occurred in the presence of steam which resulted in high concentrations of H_2 and CO_2. Over the optimum range a decreasing trend was observed in the gas yield, LHV and carbon conversion efficiency due to the low reaction temperature caused by low temperature steam. Qin et al. [44] investigated the effect of SB on tar formation and the corresponding tar properties. In their experiments, SB was varied in the range of 0.49–2.66 at 900 °C. The results revealed that as the SB was increased, the tar yield gradually decreased from 3.87 to 1.71%. It was also concluded that high SB values lower the aromacity of the tar. Another set of experiments was conducted by Gil et al. [41] who studied the effect of steam–oxygen gasification on product distribution. In their experiments, steam to oxygen and steam–oxygen to biomass ratios were varied in the range of 2–3 mol/mol and 0.6–1.6 kg/kg, respectively. The achieved results revealed that the H_2 content of the producer gas was in the range of 14–30 vol.% and decreased as the steam–oxygen to biomass ratio was increased or the steam to oxygen ratio was gradually decreased. As the O_2 introduced into the system was increased, more H_2 was burnt in the gasifier and less was found in the effluent stream. Similar trend was observed for CO while varying the defined ratios and its concentration in the producer gas was obtained in the range of 30–50 vol.%. The tar content of the raw gas clearly reduced to less than 10 g/m^3 as the steam–oxygen to biomass ratio was increased to 1.0–1.1 kg/kg. The char yield also decreased to 10% while the gasifying agent to biomass ratio was increased to the values higher than 1.0.

As mentioned earlier, steam gasification can provide a gas stream with high content of H_2, but the concentration of the undesirable products such as CO_2 is also increased. In order to improve the efficiency of the steam gasification process, considerable efforts have been devoted to the production of producer gas with high yield of H_2 with simultaneous capture of CO_2. For this purpose, Weerachanchai et al. [21] used limestone (CaO) as the bed material to capture CO_2 in steam gasification process according to the following reaction:

$$CaO + CO_2 \rightarrow CaCO_3 \qquad \Delta H = -170.5\ \mathrm{kJ/mol}$$

They obtained a gas product containing 38.71 mmol/g H_2 and 20.21 mmol/g CO_2. They explained that the significant increase in the CO_2 and H_2 concentration was attributed to the char decomposition, steam reforming reactions of hydrocarbons and tars and also water-gas shift reaction. The CO generated through char decomposition and steam reforming reactions was consumed by water-gas shift reaction to yield more CO_2 and H_2.

2.4. Effect of biomass size

It has been accepted that small particle size biomass significantly increases the overall energy efficiency of the gasification process, but it also increases the gasification plant cost. It has been estimated that for a 5–10 MWe gasification plant, about 10% of the output energy is required for the biomass particle size reduction [8,45]. On the other hand, an increase in biomass particle size reduces the pre-treatment costs, but the devolatilization time increases, and thus for a defined throughput the gasifier size increases [45]. Therefore, a balance should be considered while investigating the effect of biomass particle size on the gasification efficiency.

Lv et al. [18] investigated the effect of biomass size on the quality of the producer gas in four ranges of 0.6–0.9, 0.45–0.6, 0.3–0.45 and 0.2–0.3 mm. They observed that small particle size biomass produced more CH_4, CO and C_2H_4 and less CO_2 in comparison to large particles. Thus, the producer gas yield, LHV and carbon conversion were improved as the biomass particle size decreased. It was explained that small biomass particles contribute to large surface area and high heating rate which in turn produce more light gases and less char and condensate. Therefore, the yield and composition of the producer gas improved while using the small particle biomass. Similar results were obtained by Jand and Foscolo [46] who studied the effect of wood particle size (5–20 mm) in a fluidized bed. They also observed that increasing the particle size reduced the CO and carbon content of the producer gas while the amount of residual char and CO_2 increased. This increase was justified by the tendency of large particle to char combustion and instantaneous release of CO_2 during the combustion.

3. Types of fluidized beds

So far, fluidized beds have found limited applications in coal gasification because of their low carbon conversion efficiency which is resulted from their relatively low bed temperatures (800–1000 °C) [47]. However, fluidized beds are promising for lignocellulosic biomass due to their lower gasification temperature compared to that of coal. Also, most of problems involved in fixed beds and updraft moving bed gasifiers have been obviated in fluidized beds. Therefore, lots of current development activities on large scale biomass gasification have been devoted to fluidized bed technologies. Various types of fluidized bed have been explored in the biomass gasification process. Bubbling fluidized beds (BFB) and circulating fluidized beds (CFB) are two major types implemented for this purpose [47,48].

3.1. Bubbling fluidized bed

Bubbling fluidized bed gasification is the simplest and probably the most cost-effective concept for continuous biomass gasification. BFBs are flexible to a wide variety of biomass with various particle sizes including pulverized biomass. They provide a high rate of heat transfer between bed materials and fuel and exhibit a nearly uniform temperature distribution throughout the reactor. They are also able to generate a uniform producer gas with low content of tar and unconverted carbon [49,50]. BFBs have been extensively applied for biomass gasification and various researches have been conducted in this field. However, the optimized parameters differ in various investigations according to the desired output of the project. Table 2 summarizes several investigations conducted on BFBs; also the optimum operation parameters and results are reported.

High solid conversion is not attainable in BFBs due to the back mixing of solids. Although the high degree of mixing improves the gasification process, but intimate mixing of the fully and partially gasified fuels results in a solid stream containing partially gasified particles which reduces the solid conversions [47]. The other problem involved in BFB is the slow oxygen diffusion rate which creates an oxidizing condition in the whole bed reducing the gasification efficiency. Such inherent limitations of BFBs have been obviated in circulating fluidized bed by providing longer solid residence time through a solid circulating loop [47].

3.2. Circulating fluidized beds

In circulating fluidized bed gasification, the high fluidization velocity provides a turbulent flow regime which entrains the bed particles and char in the gas stream. As a result, a circulating

Table 2
Various investigations conducted on bubbling fluidized beds.

System configuration and operation parameters		Investigated parameters	Optimum obtained results	Ref.
Wood pellet ID: 0.15 m H: 2.15 m BM: ofite	FR: 10–21.6 kg/h GA: air + oxygen + steam BT: 755–840 °C SB: 0–0.63 ER: 0.24–0.38	Effect of air enrichment (O_2 was increased from 21 to 40 vol.%) on: Gasification efficiency LHV of the producer gas Carbon conversion	Dry gas composition (vol.%): CO: 28.5; H_2: 25.7; CO_2: 9.2; CH_4: 8.1 Gasification efficiency: 68% LHV (MJ/m^3 dry gas): 9.28 Carbon conversion: 97% Gas yield (m^3 gas/kg biomass): 0.96	[40]
Rice husk ID: 0.255 m H: 2.7 m BM: alumina sand	FR: na GA: air BT: 600–830 °C ER: 0.25–0.35	Effects of fluidization velocity (0.22, 0.28, 0.33 m/s) and ER (0.25, 0.30, 0.35) on: Producer gas composition LHV of the producer gas Gas yield Carbon conversion	Fluidization velocity: 0.22 m/s ER: 0.25 Gas composition (vol.%): CO: 19.9; H_2: 4.0; CO_2: 14.45; CH_4: 2.9; N_2: 56.57; C_nH_m: 2.14 LHV (MJ/m^3 dry gas): 5.03 Carbon conversion: 76% Gas yield (m^3 gas/kg biomass): 1.05	[43]
Pine sawdust ID: 40 mm H: 1.4 m BM: silica sand	FR: 0.3–1.0 kg/h GA: air + steam BT: 700–900 °C ER: 0.19–0.27 SB: 0–1.35	Effects of bed temperature, ER, SB and biomass particle size on: LHV of the producer gas Gas yield Carbon conversion	BT: 800 °C (gas LHV: 8.56) ER: 0.21 (gas LHV: 8.84) SB: 1.35 (gas LHV: 9.14) Feed particle size: 0.2–0.3 mm (gas LHV: 8.74) Maximum carbon conversion: 95.1% Maximum gas yield (m^3 gas/kg biomass): 2.57	[18]
Pine sawdust ID: 6 cm H: 0.7 m BM: silica sand	FR: 0.4–0.8 kg/h GA: air BT: 700–850 °C ER: 0.26–0.47	Effects of ER, bed temperature and H/C ratio in the feed on tar content of the producer gas	ER: 0.26 (tar (g/m^3): 2.01) BT: 790–800 °C H/C of the biomass: 2.1 Maximum LHV (MJ/m^3 gas): 6.3 Maximum gas yield (m^3 gas/kg biomass): 2.1	[31]
Pine wood chips ID: 15 cm H: 3.2 m BM: silica sand	FR: 5–20 kg/h GA: steam + oxygen BT: 780–890 °C ($O_2 + H_2O$)/biomass: 0.6–1.6 kg/kg H_2O/O_2: 2–3 mol/mol	Effects of bed temperature, H_2O/O_2 feeding ratio and gasifying agent to biomass ratio on: Tar content of producer gas LHV of the producer gas Gas yield	($O_2 + H_2O$)/biomass: 0.8–1.2 H_2O/O_2: 3 mol/mol Minimum tar content (g/m^3): 5 Maximum LHV (MJ/m^3 gas): 15.8 Maximum gas yield (m^3 gas/kg biomass): 1.2	[19,41]
Spruce wood pellet ID: 140 mm H: 1010 mm BM: quartz, olivine, dolomite, Ni-alumina	FR: 0.75 kg/h with N_2 GA: air + steam BT: 780 °C ER: 0.17 SB: 0.65 FV: 0.3 m/s	Effects of various catalysts on: Composition of the producer gas Tar content of the producer gas	Ni-alumina was the best catalyst Molar gas composition (%): CO: 17.6; H_2: 30.3; CO_2: 14.3; CH_4: 1.49; C_nH_m: 0.02 Heavy tar content (g/m^3): 7.6 Light tar content (g/m^3): 1.0 Gas yield (m^3 gas/kg biomass): 1.2	[19]
Radiata pine ID: 22 mm H: 500 mm BM: Co/MgO (0–36 wt% Co)	FR: 0.12–0.12 g/min GA: steam BT: 600 °C SB: na	Effect of catalyst on tar reduction	12 wt% Co/Mg exhibit the best catalytic performance Tar conversion: 16% Tar content with catalyst (g/m^3): 8.4	[51]
Pine wood chips ID: 15 cm H: 3.2 m BM: calcined dolomite	FR: 10 kg/h GA: steam + oxygen BT: 795–835 °C ($O_2 + H_2O$)/biomass: 0.7–1.2 kg/kg H_2O/O_2: 2–3 mol/mol	Effects of gasifying agent and bed material on: H_2 and CO of the producer gas Tar content of the producer gas	($O_2 + H_2O$)/biomass: 0.9–1.15 Tar content reduced from 12 to 2–3 g/m^3 H_2 content increased from 25 to 48 (vol.%) CO content decreased from 45 to 27 (vol.%) LHV reduced from 15 to 12.3 (MJ/m^3 gas) in presence of catalyst	[52]
Pine sawdust ID: 40 mm H: 1400 mm BM: calcined dolomite	FR: 0.47 kg/h GA: air BT: 800 °C ER: 0.3	Effect of catalyst on producer gas composition	Gas composition (vol.%): CO: 24.89; H_2: 38.38; CO_2: 27.62; CH_4: 7.02; C_nH_m: 2.09 Gas yield (m^3 gas/kg biomass): 1.56 Tar yield (g/kg biomass): 13.85	[53]
Wood chips ID: 400 mm H: 3 m BM: silica sand	FR: 130 kg/h GA: air BT: 718–733 °C ER: 0.17–0.23 FV: 0.24 m/s	Evaluation of thermal energy output and efficiency	Bed temperature: 733 °C ER: 0.23 LHV (MJ/m^3 gas): 4.74 Thermal efficiency: 61.23% Thermal output: 355.55 kW	[54]
Coffee ground (6–15 wt%) + coal ID: 22 cm H: 400 cm BM: na	FR: 8 kg/h GA: steam + air BT: 795–835 °C SB: 0.1–0.8 Air/fuel: 2–3 kg/kg	Evaluation of co-gasification for production of producer gas	6 wt% biomass + coal SB: 0.26 Air/fuel: 2.3 Gas composition (vol.%): CO: 8.2; H_2: 14.0; CO_2: 8.0 Maximum LHV (MJ/m^3 gas): 4.4 Maximum gas efficiency: 61%	[16]
Pine (20 wt%) + coal (40 wt%) + plastic waste (20 wt%) ID: 0.5 m H: 3.2 m BM: na	FR: 3.3–5.5 kg/h GA: steam + air BT: 750–900 °C O_2/fuel: 0.03–0.33 kg/kg O_2/steam: 0.02–0.28 kg/kg	Effect of bed temperature on producer gas composition in co-gasification of coal and waste	Bed temperature: 900 °C O_2/fuel: 0.33 kg/kg O_2/steam: 0.28 kg/kg Increasing the BT from 750 to 890 °C, promoted H_2 production by 70% and reduced CH_4 and other hydrocarbon production by 30 and 36%, respectively	[37]

Table 2 (*Continued*)

System configuration and operation parameters		Investigated parameters	Optimum obtained results	Ref.
Larch wood ID: 4.2 cm H: 57.5 cm BM: calcined limestone or calcined waste concrete or silica sand	FR: 0.21 g/min GA: steam BT: 650 °C or750 °C SB: na	Effects of various bed materials on: Producer gas composition Cold gas efficiency LHV of the producer gas	Calcined limestone was the best catalyst Bed temperature: 750 °C Gas composition (vol.%): CO: 7.71; H_2: 55.97; CO_2: 29.23; CH_4: 5.72; C_nH_m: 1.38 LHV (MJ/kg): 15.68 Carbon conversion: 96.95% Cold gas efficiency: 79.61% Gas yield (cm^3 gas/g biomass): 1549	[21]
Coal + pine sawdust + rice straw ID: 120 mm H: 1578 mm BM: na	FR: coal (2–3 kg/h); pine (0–1 kg/h) GA: steam + air + oxygen BT: 940–1020 °C ER: 0.3–0.42 SB: na Steam/carbon: 51 kg/kg	Effects of ER and biomass/coal ratio on: Yield of the producer gas H_2 and CO content of the producer gas	Coal (2 kg/h) + pine sawdust (1 kg/h) Bed temperature: 953 °C ER: 0.34 Gas composition (vol.%): CO: 29.13; H_2: 20.71; CO_2: 19.43; CH_4: 2.54; N_2: 28.20 Carbon conversion: 88.89% Gas efficiency: 60.92% Gas yield (m^3 gas/kg biomass): 2.01	[17]
Sawdust ID: 34 mm H: 500 mm BM: na	FR: 0.5 g/min GA: air + steam BT: 800 °C or 900 °C ER: 0.21–0.22 SB: 0.61–2.7 (800 °C); 0.49–2.66 (900 °C)	Effect of SB on tar yield of the producer gas	BT: 800 °C, SB: 2.7 (tar yield: 2.31%) BT: 900 °C, SB: 2.66 (tar yield: 1.71%)	[44]
Pine chips + coal (ratio 0–100) ID: 43 mm H: 2000 mm BM: na	FR: 1.23 kg/h GA: air + steam BT: 840–910 °C SB: 0.51 Air/feed: 0.89 (m^3/kg)	Effect of biomass/coal ratio on: Overall thermal efficiency LHV of the producer gas Yield of producer gas	Pine chips to coal: 25/75 Molar gas composition: CO: 16.81; H_2: 13.05; CO_2: 8.39; CH_4: 1.63; N_2: 59.13; C_nH_m: 0.31 Carbon conversion: 75.3% LHV (MJ/m^3 gas): 4.29 Gas yield (m^3 gas/kg biomass): 2.46 Thermal efficiency: 61%	[55]
Olive kernel ID: 60 mm H: 90 mm BM: olivine	FR: 120 g/min GA: air BT: 750–850 °C ER: 0.2–0.4	Effect of bed temperature and ER on the quality of the producer gas	Bed temperature: 750 °C ER: 0.2 Gas composition (vol.%): CO: 14.26; H_2: 23.98; CO_2: 19.42; CH_4: 3.75; C_nH_m: 1.81 LHV (MJ/m^3 gas): 6.54	[34]
Rice husk ID: (bottom: 1.4 m; top: 2 mm) H: 8.5 m BM: na	FR: 400–1500 kg/h GA: air BT: 680–810 °C ER: 0.18–0.27	Effect of bed temperature, feeding rate and biomass water content on the LHV of the producer gas	Bed temperature: 700–800 °C FR: 1400 kg/h Gas composition (%): CO: 16–21; H_2: 5–8; CO_2: 15–16; CH_4: 4–6; C_nH_m: 2 LHV (MJ/m^3 gas): 5.45–6.40 Feed moisture content < 15%	[36]
Pine sawdust + coal + plastic waste ID: 9.2 cm H: 2 m BM: dolomite	FR: 1–4 kg/h GA: air BT: 750–880 °C ER: 0.3–0.46	Effect of bed temperature, ER and feed composition on: LHV of the producer gas Tar content of the producer gas Producer gas composition	ER: 0.36 Bed temperature: 850 °C Pine, coal, plastic waste ratio: 20/60/20 Gas composition (%): CO: 10–20; H_2: 7–15; CO_2: 14–23; CH_4: 2–10; C_nH_m: 1–5 LHV (MJ/m^3 gas): 4–8 Gas yield (m^3 gas/kg biomass): 1.5–5 Minimum tar content (g/m^3): 0.5	[56]
Coconut shell ID: 10 cm H: 92 cm BM: Ni-dolomite	FR: 0.5 g/min GA: steam BT: 600–800 °C Steam/C: 0.2–1	Effects of bed temperature and steam to carbon ratio on producer gas composition and tar reduction in presence of catalyst	Bed temperature: 800 °C Steam/C: 0.95 Gas composition (vol.%): CO: 35.72; H_2: 38.74; CO_2: 29.9; CH_4: 4.5 Carbon conversion: 78.43% Tar yield: 1.44%	[38]
Distillers grains ID: 3.81 cm H: 1200 mm BM: sand	FR: 1–1.5 kg/h GA: steam + air BT: 650–850 °C ER: 0.07–0.29 SB: 0–14.29	Effects of bed temperature and SB ratio on: H_2 content of the producer gas Carbon conversion Energy conversion efficiency	BT: 850 °C SB: 7–11 Hydrogen of the producer gas content: 15% Carbon conversion: 82% Energy efficiency: 96%	[39]
Cedar wood ID: 15 mm H: 66 cm BM: $Rh/CeO_2/SiO_2$	FR: 150 mg/min GA: air BT: 550–700 °C ER: 0.25	Comparison of the performance of the fabricated catalyst in a single and dual catalytic bed gasifier	Single catalytic bed was preferred Carbon conversion: 99% Tar yield: 0% Char yield: 1%	[57]
Cedar wood OD: 100 mm H: 1200 mm BM: $Rh/CeO_2/SiO_2$	FR: 150 mg/min GA: air BT: 550–700 °C ER: 0.28	Effect of the fabricated catalyst on: Tar reforming of the producer gas	Bed temperature: 700 °C Carbon conversion: 99% Tar yield: 0% Cold gas efficiency: 82%	[58,59]
Bagasse ID: 89 mm H: na BM: na	FR: 1.03 kg/h GA: air BT: 800 °C ER: 0.27	Characterization of the producer gas for condensable hydrocarbon species and ammonia	Gas composition (vol.%): CO: 16; H_2: 10.8; CO_2: 15.9; CH_4: 4.3, N_2: 50.8; C_nH_m: 2.12 Gas yield (m^3 gas/kg biomass): 1.9 Oil and tar content (g/m^3): 14.8 Ammonia content of the producer gas (ppm): 930	[60]

Table 2 (*Continued*)

System configuration and operation parameters		Investigated parameters	Optimum obtained results	Ref.
Wood sawdust ID: 15 mm H: 66 cm BM: silica sand	FR: na GA: air BT: 750 °C Air/wood: 2.35 (m^3/kg)	Determination of the optimum operation parameters	Gas composition (%): CO: 9.25; H_2: 9.27; CO_2: 13.28; CH_4: 4.21, N_2: 62.47; C_nH_m: 1.53 Gas yield (m^3 gas/kg biomass): 2.99 Carbon conversion: 87.1% LHV (MJ/m^3 gas): 4.97 Cold gas efficiency: 56.9% Tar content (mg/m^3): 10	[14]
Almond shell ID: 60 mm H: na BM: olivine, dolomite, sand	FR: 0.3 kg/h GA: steam BT: 770 °C SB: 1	Comparison the effect of various bed materials on the quality of the producer gas	Gas composition with olivine (vol.%): CO: 23.0; H_2: 52.2; CO_2: 16.9; CH_4: 7.9 Gas yield (m^3 gas/kg biomass): 1.7 LHV (MJ/m^3 gas): 11.37 Char yield (g/kg biomass): 36 Gas composition with dolomite (vol.%): CO: 24.0; H_2: 55.5; CO_2: 14.1; CH_4: 6.4 Gas yield (m^3 gas/kg biomass): 1.9 LHV (MJ/m^3 gas): 10.93 Char yield (g/kg biomass): 30 Gas composition with sand (vol.%): CO: 33.2; H_2: 43.6; CO_2: 11.7; CH_4: 11.5 Gas yield (m^3 gas/kg biomass): 1.1 LHV (MJ/m^3 gas): 13.02 Char yield (g/kg biomass): 102	[61]
Coconut coir ID: 60 mm H: 425 mm BM: na	FR: 0.3 kg/h GA: air BT: 700–900 °C ER: 0.16–0.46	Effect of bed temperature and ER on the LHV and yield of the producer gas	LHV (MJ/m^3 gas): 2.38 at 900 °C Gas yield (mol gas/kg biomass): 2.95 at 900 °C LHV (MJ/m^3): 0.47 at ER of 25 Gas yield (mol gas/kg biomass): 1.08 at ER of 25	[62]

H: height of gasifier, ID: internal diameter, BM: bed material, GA: gasifying agent, FR: feeding rate, ER: equivalence ratio, SB: steam to biomass ratio, BT: bed temperature, FV: fluidization velocity, na: data were not available.

stream is created through which the entrained particles leave the top part of the reactor and enter into another unit. In external circulating fluidized beds (ECFB), the effluent stream of the gasifier enters into a cyclone. The solid particles are captured in the cyclone, separated from the gas phase and finally returned to the gasifier. This process which extends the solids residence time is performed repeatedly while operating the gasifier [49]. One of the disadvantages involved with ECFB gasifiers is the need to add solid separation and return equipments which increases the investment costs as well as process controlling problems [63].

Internal circulating fluidized beds (ICFBs) are another type of CFBs which have attracted considerable attention for biomass gasification in recent years. Generally, ICFB is consisted of two separate chambers; one is functioning as a bubbling turbulent fluidized bed gasifier and the other acts as a pneumatic riser combustor. The chambers contain bed materials which circulate between the two chambers and create a circulating flow through which the char and other gasification residues are transferred to the combustion chamber. Airflow is supplied to the combustor as an oxidant to conduct the char combustion. The combustion of char provides heat which is useful for the bed materials. The heated bed materials which are transferred from the combustion chamber to the gasification reactor act as external heat source to supply the required energy for endothermic steam gasification. This type of gasifiers has sometimes been named as dual fluidized bed as they consist of a BFB gasifier and a CFB combustor. Table 3 presents various investigations conducted on biomass gasification in CFBs. Also, numerous approaches have been found in the literature on simulation and modeling of CFBs which facilitate the optimization of the operation parameters as well as their design and scale-up [20,64–75].

Although CFBs have not been demonstrated as BFBs, they offer some advantages over BFBs due to their high heat and mass transfer and long residence time. The high stream velocity and recirculation in CFBs provide appropriate mixing and contact time which boosts the heat and mass transfer within the gasifier. As a result, a suitable environment is created for gasification and the quality of the producer gas is improved [47]. Another advantage of CFB over BFB is the prolonged catalytic activity. In BFBs, fouling which is caused by deposition of carbon on the catalyst surface causes a rapid loss of catalytic activity. This problem would be eliminated in CFBs due to the burning out of the deposited carbon in the circulation process. Besides, the circulation of the bed materials which act as heat carrier compensate the heat consumed in the endothermic reactions involved in gasification process [28,66].

4. Industrial plants

Biomass gasification for production of energy and biofuel is one of the effective ways to utilize biomass resources. The producer gas obtained from the gasification process may be cleaned and used to run internal combustion engines or to provide valuable liquid or gaseous biofuels. Biomass gasification plants operating at atmospheric pressure coupled with internal combustion engines, combustion turbine, steam turbine or fuel cells actualize the dream of waste-to-energy plants. Such plants may be established and operated close to the origin of the biomass wastes, thus providing the requirements of such regions. These units can be operated with fuel of low heating value, typically the producer gas originated from biomass gasification.

In the past decade, many facilities regarding to renewable energy development policies have been implemented worldwide. Currently, biomass fuels provide 14% of the world energy demand. Biomass supplies 4% of the primary energy consumed in United State, 17% in Finland and 21% in Sweden [49]. Table 4 presents some of the industrial biomass gasification plants using fluidized bed gasifiers.

Commercialized production of various transportation fuels from coal and natural gas has been well demonstrated by Sasol and Mobil plants [79]. However, such process is not yet established for biomass due to the difficulties in synthesis gas production and clean-up and also low heating value of the product gas in comparison to natural gas. Thus, the governments' incentive on

Table 3
Various investigations conducted on circulating fluidized beds.

System configuration and operation parameters		Investigated parameters	Optimum obtained results	Ref.
Wood pellet ID: na H: na BM: olivine or calcite	FR: 25 kg/h GA: steam BT: 841 °C (olivine) 645 °C (calcite) SB: 0.63 (olivine) 0.79 (calcite)	Comparison of the performance of two different bed materials on: Composition of the producer gas Total energy output	Gas composition with olivine (vol.%): CO: 29.1; H_2: 39.1; CO_2: 17.5; CH_4: 11.4; C_nH_m: 2.9 Tar content with olivine (g/m^3): 3.53 Total energy output with olivine (kW): 161.5 Gas composition with calcite (vol. %): CO: 6.1; H_2: 73.9; CO_2: 6.0; CH_4: 11.4; C_nH_m: 2.3 Tar content with calcite (g/m^3): 1.4 Total energy output with calcite (kW): 145.1	[65]
Coffee ground Gasifier: two-stage BFB H: 1980 mm Cross-section 1: 80 mm × 370 mm Cross-section 2: 180 mm × 370 mm Combustor: riser ID: 52.7 mm H: 6400 mm BM: silica sand	FR: 4 kg/h GA: steam BT: 820 °C CT: 830 °C SB: 1.1	Evaluation of the performance of a two-stage dual fluidized bed gasifier	Molar gas composition (%): CO: 28.2; H_2: 31.2; CO_2: 17.3; CH_4: 13.6; C_nH_m: 9.61 H_2/CO: 1.106 LHV (MJ/m^3): 15.23	[7,76]
Coffee ground Gasifier: BFB H: 1800 mm Cross-section: 80 mm × 370 mm Combustor: riser ID: 52.7 mm H: 6400 mm BM: silica sand	FR: 3.6 kg/h GA: steam BT: 800 °C CT: 830 °C SB: 1	Evaluation of the performance of a dual fluidized bed gasifier	Molar gas composition (%): CO: 38.2; H_2: 19.3; CO_2: 9.5; CH_4: 17.5; C_nH_m: 15.5 Product distribution (wt%): gas: 75; char:22.1; tar: 2.9	[20]
Woody biomass Gasifier: CFB ID: 20 cm H: 6 m BM: silica sand	FR: 50–100 kg/h GA: air BT: 800–860 °C ER: 0.37	Evaluation of the performance of the CFB gasifier using several feedstock	The average of some important parameters: Carbon conversion: 92% C-balance: 98% Cold gas efficiency: 61% Fuel-N to NH_3 conversion: 62% Heavy tars (mg/m^3): 270	[77]
Rice husk and sawdust Gasifier: ICFB ID: na H: na BM: quartz sand0	FR: na GA: air BT: na ER: 0.22–0.26 (risk husk) ER: 0.17–0.24 (sawdust)	Evaluation of the effect of ER and fluidization velocity	Rice husk: LHV (MJ/m^3): 5 Maximum gasification efficiency: 77% at ER = 0.28 Sawdust: LHV (MJ/m^3): 6–6.5 Maximum gasification efficiency: 81% at ER = 0.25	[63]
Sawdust Gasifier: CFB H: 6.5 m ID: 0.1 m BM: Ni-alumina	FR: 41 kg/h GA: air BT: 700–850 °C	The effects of bed temperature and catalyst on: Composition and heating value of the producer gas Tar yield	Bed temperature: 800 °C Tar yield (g/m^3): 2.35 Catalyst (kg): 11–14 Gas composition (%): CO: 17.9; H_2: 7.3; CO_2: 16.3; CH_4: 3.2; N_2: 55.4 LHV (MJ/m^3): 4.6 Gas yield (m^3 gas/kg biomass): 2.35 Cold gas efficiency: 60.5% Carbon conversion: 94.9%	[35]
Wood powder Gasifier: CFB H: 4000 mm ID: 410 mm BM: na	FR: 210 kg/h GA: air BT: 630–1042 °C ER: 0.17–0.28	Effect of ER on the composition of the producer gas	ER: 0.25 BT: 974 °C Gas composition (%): CO: 16.7; H_2: 16.32; CO_2: 15.6; CH_4: 6.9; N_2: 43.25; C_nH_m: 1.0 LHV (MJ/m^3): 7.2 Energy output (kW): 743 Carbon conversion: 92.8% Heat efficiency: 74.6% Gas yield (m^3 gas/kg biomass): 1.927	[78]

H: height of gasifier, ID: internal diameter, BM: bed material, GA: gasifying agent, FR: feeding rate, ER: equivalence ratio, SB: steam to biomass ratio, BT: bed temperature, FV: fluidization velocity, CT: combustor temperature, na: data were not available.

investment in this field is not consistent and varies by the situation of the fossil fuel market. But, there is a rising interest in developed countries to produce biofuels from biomass and wastes, especially for transportation sector. For example, the European parliament has approved to increase the contribution of biofuels in transportation fuels including petrol and diesel to 5.7% in 2010 and 10% in 2020 [79]. Currently, there exist a market for bioethanol and biodiesel as potential automotive fuels in modern countries. However, these biofuels are mostly derived from food crops such as corn and vegetable oils. Considering just the production cost of such food crops boosts the preference of woody and grassy materials as well as agricultural residues as potential feedstock for biofuel. Thus, production of transportation fuels such as bioethanol, biomethanol, Fischer–Tropsch fuels and hydrogen via gasification along with consequent synthesis process (Fischer–Tropsch synthesis, steam reforming and/or fermentation) is a promising technology from the both economical and environmental points of view.

Table 4
Various industrial plants on biomass gasification using fluidized bed.

Developer	Gasifier type	Feed stock	Feed rate (ton/day)	Gas output rate (m^3/h)	LHV (MJ/m^3)	Power/heat generation	Investment cost ($ MM)	Ref.
Battelle Columbus Laboratory	CFB (steam)	Woody biomass	26	na	18	na	25.2	[49]
TPS-Thermal Process Studsvik	CFB (air)	Wood	13	800	4–7	na	27.5	[49]
Lurgi Energy	CFB (air)	Bark	90–120	9700–12,500	5.8	na	8.7	[49]
Alternate Gas	BFB (hot air)	Wood chips	200	4845	5.62–8.25	na	11.1	[49]
Foster Wheeler	CFB (air)	Wood	16	1181	7.5	na	na	[49]
Energy Products of Idaho	BFB (air)	Wood chips	110	8793	5.6	na	2.1	[49]
BECON	BFB (air)	Shelled corn	5	200	4.5	na	na	[49]
Carbona-Skive	FBG (air, steam)	Wood pellets	110	na	5.5	5.5 MW_e/11.5 MW_{th}	na	[49]
Varnamo plant	CFB (air)	Wood chips	96	na	5	6 MW_e/9 MW_{th}	na	[80]
Changxing Zhejiang province	FBG (air)	Rice husk	9.6–36	500–3000	5.4–6.4	1.2 MW	na	[36]

5. Conclusion

Finding alternative energy resources is of utmost importance. Recently, considerable attentions have been paid to biomass gasification technologies due to their potential to convert biomass waste to bioenergy and biofuels. So far, numerous researches have been conducted on gasification of lignocellulosic biomass using fluidized bed and various operation parameters have been investigated to improve the effectiveness of the gasification plants. The great ability of fluidized beds to conduct the gasification process has been confirmed by many researchers as well as several successful operating industrial plants in developed countries. However, more research is required to see extensive and flourishing progress in this area in the future.

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